

# Comparative Analysis of Thermal Conversion Technologies for Deep Space Missions

Parisa M. Mirdamadi<sup>1</sup>, Sabah K. Bux<sup>2</sup>, and Laura J. Evans<sup>3</sup>

<sup>1</sup>Universities Space Research Foundation, Cleveland, OH, 44135

<sup>2</sup>Jet Propulsion Laboratory/California Institute of Technology, Pasadena, CA, 91109

<sup>3</sup>NASA Glenn Research Center, Cleveland, OH, 44135

Primary Author Contact Information: (818) 393 7067, Sabah.K.Bux@jpl.nasa.gov

[Placeholder for Digital Object Identifier (DOI) to be added by ANS]

*Radioisotope power systems (RPS) utilizing Plutonium-238 as a heat source for thermal-to-electric energy conversion have been used as a reliable power source for NASA's deep space missions for sixty years. Recent innovations and improvements to thermal energy technologies show potential increases to radioisotope system efficiencies from current measurements of ~5-7% to efficiencies upwards of 20%. This report surveys and ranks recent, innovative thermal-to-electric energy conversion research technologies. Technologies being developed at universities and industry are compared with respect to thermal conversion method and relevant key performance parameters. Key performance parameters are identified as system specific power per kg, efficiency, power output, technology readiness level, and system mass. Analytical Hierarchy Process (AHP) was utilized to create weighted values for each evaluation criterion. The AHP tables combined with decision matrices create table scores for past, present, and potential future systems. The table score was combined with a conversion method score in an adjustable system to add value to flight-proven or well-tested thermal conversion technologies such as thermoelectrics. While the three highest-ranking systems reviewed are currently being developed by NASA's RPS Program, the additional highest-ranking systems not under-development by RPS could warrant further research.*

## I. INTRODUCTION

Radioisotope thermoelectric generators (RTGs) have been used by NASA to provide a stable source of power for probes and rovers sent into deep space for over sixty years. Their long-term reliability and continued power production in environments lacking sufficient sunlight for solar power systems makes this power source highly important to the future of space exploration. The natural alpha-decay of Plutonium-238 generates heat regardless of day and night cycles, dust on terrestrial surfaces, or if the device is in a shadowed location. RTGs utilize the Seebeck effect to generate power, which states that the temperature gradient across two materials produces a voltage. Thermocouples are made of high-ZT materials

such as silicon-germanium alloys or tellurium based-alloys to convert the heat to electricity. A low thermal conductivity, low electrical resistivity, high Seebeck coefficient ( $\Delta V/\Delta T$ ) and wide operating temperature range ( $\Delta T$ ) may increase the ZT value and system efficiency.

NASA's Radioisotope Power Systems (RPS) Program invests and manages space nuclear power for the Science Mission Directorate. The Technology Management (TM) element of RPS manages research and development of technologies that advance RPS goals, show promise as a part of potential flight systems, and provide sustainment to critical government and commercial RPS capabilities.

In order to evaluate and inform future investments by TM, a comparative analysis of current RPS and TM investments and potential new technologies was performed by establishing a set of criteria using the analytical hierarchy process (AHP) to determine weighted values indicating the relative value of each criterion. Decision matrices and tables of numerical system data use the AHP weights to determine which option in a set of data warrants further investigation. The table score is given based off previously established criteria weights, and the result is combined with an overall conversion method score to get a final value. The conversion method score is implemented to add consideration and value to flight-proven systems for modularity, reliability, and flight-readiness.

## II. OVERVIEW OF RADIOISOTOPE POWER SYSTEMS

RPS systems can be separated into solid-state and dynamic systems. Historically, silicon germanium has been used as the thermoelectric material of choice for RTGs. A typical solid-state system is easy to use after fueling, has no moving parts, has a relatively low conversion efficiency, and produces a large amount of waste heat (Ref. 1). Other solid-state RPS technologies include thermionic and thermophotovoltaic systems. Dynamic systems, such as Stirling, Thermoacoustic, Brayton and Rankine boast high conversion efficiencies

upward of 30%, have generally higher power output, and utilize moving parts. The Stirling system uses pistons, for example, while the Brayton system uses gas as a working fluid. A dynamic system has not yet flown in space. A general-purpose heat source (GPHS) unit houses the fuel, most often Pu-238, and several layers of shielding. Several GPHS units may be used in a modular RPS system to produce more heat for a larger system.

### **III. OVERVIEW OF THE RPS TECHNOLOGY MANAGEMENT ELEMENT**

The Technology Management element of the Radioisotope Power Systems Program Office manages and invests in developing promising thermal-to-electric conversion technologies. The technology readiness level (TRL) level of a system indicates how well-developed it is. TRL 1-4 involves proof-of-concept, modeling, and basic breadboard testing. TRL 9 is a flight proven system. The focus of this evaluation and ranking is low-TRL (TRL 1-4) technologies.

While RTGs have proven to be reliable means of converting heat to electricity for space missions, other methods of thermal energy conversion are also being developed by Technology Management. The TM element manages the Skutterudite Technology Maturation Task (STM) which is currently at a TRL 4-5. The use of skutterudite as a thermoelectric material instead of lead-telluride is expected to be used on an enhanced MMRTG (eMMRTG) (Ref. 2). Another RTG, the Next Gen-Mod 2 (NG-MOD2, TRL 2), will use segmented thermocouples and is planned to be used on an upgrade to the GPHS RTG restart in the RPS Program. The task Group for the HOListic Science of Thermoelectrics (GHOST) is TRL 1 and is focused on improving thermoelectric materials through the utilization of modeling and experimental validation. The Small Stirling Technology Exploration Power (SmallSTEP, TRL 2) task is a Stirling cycle-based conversion system for low power applications. Finally, the Radioisotope Johnson Thermo-Electrochemical Convertor (RJTEC, TRL 1-2) is a solid-state heat engine utilizing gaseous electrochemical cells and the principles of the Ericsson thermodynamic cycle for heat-to-electric conversion. GHOST is not included in the comparative analysis due to its theoretical nature and SmallSTEP is not included as its low power levels are not compatible to compare to the typical power levels for RPS systems.

Recent dynamic RPS systems under development include the Flexure-based Isotope Stirling Convertor (FISC) from American Semiconductor, the Sunpower Robust Stirling Convertor (SRSC) from Sunpower, Inc., and the Turbo-Brayton Convertor (TBC) from Creare which all produce a significantly high system efficiency.

### **IV. RANKING TECHNOLOGIES UTILIZING THE AHP**

The search for new technologies was limited to RPS technologies producing 100W to 1kW of power, but not limited by conversion method. Fission Power Systems are often used for power requirements greater than 1kW and were not considered. Very low-TRL technologies are challenging to evaluate and rank because they lack substantial testing data and are limited to predictive testing methods such as computer modeling for performance estimates which may be untenable. For this research, key performance parameters (KPP), AHP tables, decision matrices, data tables with normalized ratings, and graphical visualizations are used to rank varying potential RPS systems.

#### **IV.A. Establish Criteria / AHP Tables**

When describing RPS systems, parameters may directly influence one other. The most complete picture of a system design should be captured by the fewest parameters. The end-of-design-life parameters do not exist for many low-TRL systems, restricting KPPs to beginning-of-life (BOL) estimates. With consideration for the TRL, power values, efficiency, and system specifics, five criteria were selected. 1) TRL - The technology maturity level. This considers the time to maturation and cost of further development. 2) System Efficiency (%) - The system conversion efficiency at BOL. 3) Specific Power (W/kg) - The specific power (We/kg) of the system. It is not affected by the large (>300 W) or small (mW) scale of the system. 4) Power Output (We) - The electrical power output at beginning of life. This ignores potential mission requirements for a low or high-power system. 5) Mass (kg) - The mass of the system, accounting for the number of GPHS modules and Pu-238 (or alternative heat source.) Pairwise comparisons allow each criterion to receive a weighted value. Several responses were collected by the Technology Management (TM) element to determine criteria importance.

For TRL levels, a Gaussian distribution was used to create a bell curve with the peak value at TRL 3. TRL 1 and 2 take extensive development time and investment, while highly estimated KPP values may be untenable. TRL 4 will be costly to develop further, and the system may need to be redesigned for mission requirements, but the performance estimates are more feasible. A TRL 4 system is given a lower value specifically for these purposes of evaluating which new technology is optimal for beginning development.

The AHP tables are filled out and the answers from individuals are averaged to create a representative percentage for each criterion. The most important criterion is system efficiency at 33%, while specific power and power output are approximately 22% each. The TRL level and system mass both take approximately

10% importance each. As RPS goals and missions evolve, AHP tables can be easily modified to reflect changing priorities.

#### IV.B. Decision Matrices: Existing RTG Systems

For all data tables, entries under the Value columns are the actual proposed system estimates (e.g. the system efficiency for NG-MOD2 is 10%) whereas those under the Rating columns are normalized values later used for comparison in the decision matrices. Comparing current TM tasks to previous systems requires a scale from TRL 1-9, thus this table is the only one using a different scale for TRL than all other decision matrices. Since past and present systems are being compared directly, the TRL scale must be adjusted so that TRL 9 holds the highest value. Some parameters, like system mass, are better when the numerical value is lower. The “reverse” column in Figure 1 shows that a lower system mass is prioritized when assigning values to the mass criterion. Previous systems compared include the Multi-Hundred Watt (MHW)-RTG developed for the Voyager spacecraft, GPHS-RTG used on several past US space missions, and the European Space Agency (ESA) RTG.

Thermoelectric		Scores					
	Criteria	TRL	Sys Eff. (%)	Sp. Power (W/kg)	Mass (kg)	Power Out (We)	
	Weight	12%	33%	22%	11%	22%	Total
	MMRTG	2.5	3.8	2.2	1.5	2.1	12.1
	eMMRTG	1.1	5.1	2.6	1.5	2.3	12.5
	*eMMRTG	2.5	5.1	2.6	1.5	2.3	13.9
	MHW-RTG	2.5	4.5	3.4	1.5	2.7	14.6
	GPHS-RTG	2.5	4.4	4.1	1.4	4.9	17.3
	NG-MOD2	0.5	7.0	5.4	1.4	6.8	21.2
	ESA RTG (Am-241)	0.8	3.5	1.5	1.7	0.9	8.4

**Fig. 1.** Validating the AHP with current and prior systems.

The strongest system in Figure 1 is NG-MOD2, surpassing even the heavily favored GPHS and MHW-RTG (which have high scores primarily due to their TRL 9 status). The areas where eMMRTG excels are not captured well on this table (e.g. improved power after 17 years operation). In Figure 1, the \*eMMRTG assumes TRL 9 for the system to reflect the drop-in replacement nature of eMMRTG, and the eMMRTG row reflects current TRL 4 for the TE subsystem convertor. The numbers under TRL represent a table score which equals the normalized TRL-level value multiplied by the importance of 12% for TRL as a criterion.

#### IV.C. Decision Matrices: Existing RPS In-Development & New Options

Relevant systems were compared in three separate tables for like-to-like ranking. Tables were generated for thermoelectric generators, dynamic systems (Stirling, Brayton, Thermoacoustic, Thermo-Electrochemical), and Thermophotovoltaics (TPV)/Thermionics (TI). The

highest scoring of the newest options across all decision matrix tables were down-selected and had their values normalized for cross-comparison. Along with the low-TRL RTG systems mentioned prior (NG-MOD2, ESA RTG), highest scoring dynamic systems (TBC, European Radioisotope Stirling Generator (ERSG), FISC, Radioisotope Thermo-Acoustic Generator (RTAG) Hekyom, Thermoacoustic-Magneto Hydrodynamic (TA MHD) AREVA, RJTEC), and highest scoring TPV/TI (Radioisotope Thermophotovoltaic (RTPV) Nanophotonic, RTPV InGaAs monolithic integrated module (MIM) systems were compared. The Hybrid Thermionic-Thermophotovoltaic (TIPV) system was not included in this data table as full RPS system data is not yet available; however, estimated values were used to generate a decision matrix score for further ranking based on available information in comparison to the RTPV system.

As can be seen in Figure 2, the flight history and proven functionality of RTGs is not reflected against less-mature conversion systems like JTEC and Radioisotope Thermophotovoltaics (RTPV) when only using an AHP & Decision Matrix table. This table is optimized for low-TRL, new investments. The eMMRTG was removed because it is a higher TRL (4 or 9) and thus less comparable to new low-TRL investments. eMMRTG continues to be a great candidate for completing maturation rather than beginning investment.

Generators	Scores					
Criteria	TRL	Sys Eff. (%)	Sp. Power (W/kg)	Mass (kg)	Power Out (We)	
Weight	12%	33%	22%	11%	22%	Total
NG-MOD2	1.1	1.5	1.6	1.0	3.6	8.9
ESA RTG (Am-241)	1.4	0.7	0.5	1.1	0.4	4.2
TBC (6GPHS)	1.4	3.1	0.6	0.9	2.9	8.9
ERSG (Am-241)	1.4	3.4	0.4	1.0	0.9	7.2
FISC (6GPHS)	1.4	3.6	1.4	1.0	3.2	10.7
RTAG Hekyom (Am-241)	1.4	4.8	0.6	1.1	1.1	9.0
TA MHD AREVA	1.2	3.1	2.0	1.0	4.5	11.8
RTPV Nanophotonic	1.1	4.5	2.0	1.1	1.3	10.1
RTPV InGaAs MIM	1.1	2.7	5.4	1.2	1.2	11.6
RJTEC (3GPHS)	0.6	6.0	7.4	1.1	2.7	17.7

**Fig. 2.** Step 1 system downselection.

##### IV.C.1. Incorporating Merit for Proven Systems

Another set of values must be implemented to reflect the advantages and disadvantages of different thermal conversion methods. The symbol assignments (except TIPV and TEC) are from Mazzetti (2018) (Ref. 3). The hybrid TIPV is given a higher conversion score than TPV, but not higher than TI because it has not yet been proven in space; thermionic systems using lightweight nuclear reactors were launched under the Soviet Union. Values were assigned to each thermal conversion type for combination with Table Scores from the decision matrices.

#### IV.D. Ranking Systems

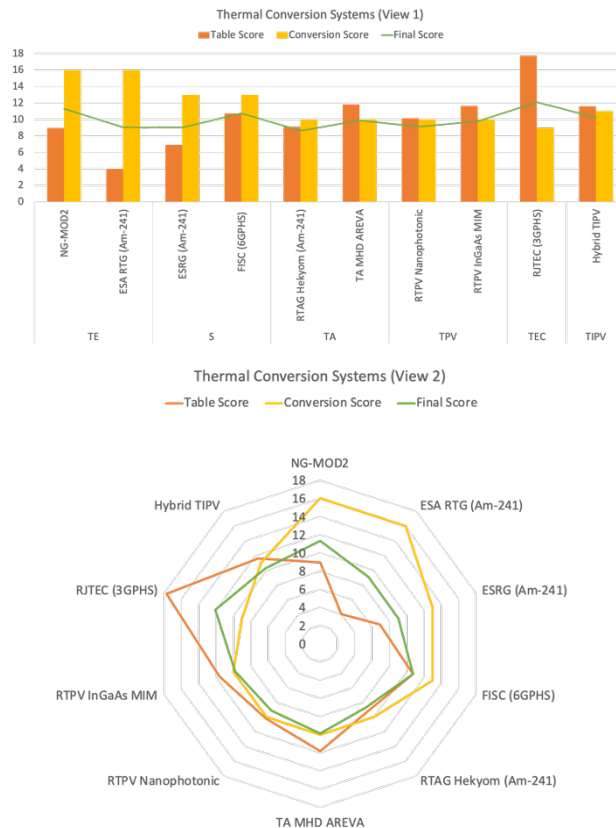
JTEC remains the highest-ranked thermal conversion technology for further development of those which have been reviewed. The final scores in Figure 3 show the adjusted combination of the prior two for a complete system review. The JTEC data was taken using projected data from 2019 NETS and classified as TRL 1 (Ref. 4). Projected data was sometimes used so that a complete system estimate remained consistent with the given TRL level.

The top three technologies are currently invested in by the RPS Program and TM. The Table Score (from numerical data, AHP and Decision Matrix) favors the low-TRL systems with very high efficiencies (JTEC, RTPV). The Conversion Score (from the Thermal Conversion Type table) favors reliable, proven systems such as RTGs and Stirling engines.

Conversion Type	System	Table Score	Conversion Score	Final Score	Rank	Currently in-development at RPS?
TE	NG-MOD2	8.9	16.0	11.29	2	Y
	ESA RTG (Am-241)	4.2	16.0	9.17	8	N
S	ESRG (Am-241)	7.2	13.0	9.13	9	N
	FISC (6GPHS)	10.7	13.0	10.73	3	Y
TA	RTAG Heptyom (Am-241)	9.0	10.0	8.62	10	N
	TA MHD AREVA	11.8	10.0	9.86	5	N
TPV	RTPV	10.1	10.0	9.09	7	N
	Nanophotonic RTPV InGaAs MIM	11.6	10.0	9.77	6	N
TEC	RJTEC (3GPHS)	17.7	9.0	12.10	1	Y
TIPV	Hybrid TIPV	11.6	11.0	10.24	4	N

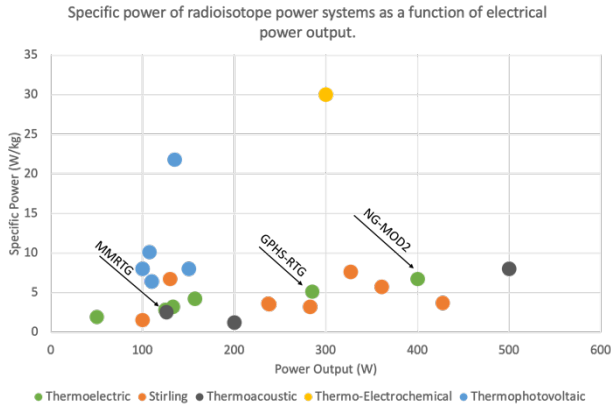
**Fig. 3.** Top ten downselected options using table score and conversion score.

The effects of both values on the final scores can be seen in Figure 4 (top) on the green line. Conversion methods with years of historical use have lower performance table scores (orange) compared to the “newer” technologies with much higher performance estimates but lower conversion scores (yellow). The green “Final Score” line is a combination of both performance estimation data and the thermal conversion method for each system. Figure 4 (bottom) provides another view of this information, where lines are pulled in the direction of highest values. Again, the Table Score is strongest near JTEC, while Conversion Score is strongest near the RTGs. The orange and yellow bars have similar maximum values, meaning they influence on the final result approximately the same amount. If the conversion method scores were assigned larger values to emphasize the lower risk of advancing systems of high TRL, low complexity, high modularity and proven life, the final green line would become more heavily biased toward historical systems such as RTGs.



**Fig. 4.** [View 1] Table data (orange), conversion method (yellow) and final scores (green) [View 2] Radar chart of system scores.

In general, specific power and power output have a positive correlation as seen in Figure 5. The RTPV systems are mostly dominant in the lower power ranges, with possibilities for higher specific power systems. Thermoelectric and Stirling systems both have a wide range of applicability, while thermoacoustic generators perform best with very high-power outputs. The TIPV system is not pictured due to lack of proposed system data, and the JTEC system is based upon values from a TRL 1 system (Ref. 4) to maintain consistency with the lower TRL system-level data.



**Fig. 5.** Specific Power vs. Power output graph for different types of systems studied.

## V. NEW SYSTEMS CONSIDERED

A modified data table for only new options to TM was created with updated normalized data. The European Space Agency (ESA) is currently developing a thermoacoustic coupled magneto-hydrodynamic (TA-MHD) power system using Americium-241. This TA-MHD system using Am-241 has been further researched and developed than the general TA-MHD for space applications described by Alemany (2011) (Ref. 5), and its resulting performance estimates may be used to suggest that the higher estimates for a system using Pu-238 are more feasible (Ref. 6). Using Pu-238 for fuel, the TA-MHD may outperform SRSC and TBC generators.

The Hybrid Thermionic-Thermophotovoltaic (TIPV) system was not included in the data table as full RPS system data is not yet available; however, estimated values were used to generate a decision matrix score based on available information. A Hybrid TIPV system has a lower TRL (1) than RTPV, possibilities to reach a similarly high efficiency (18%), but with a much higher estimated power density (6.73 W/cm<sup>2</sup>). Therefore, it was assigned a similar table score to the RTPV InGaAs Monolithic Integrated Module (MIM) system. The RTPV Nanophotonic option was dropped due to high similarities with the InGaAs MIM system. The updated decision matrix using new normalized values is shown in Figure 6.

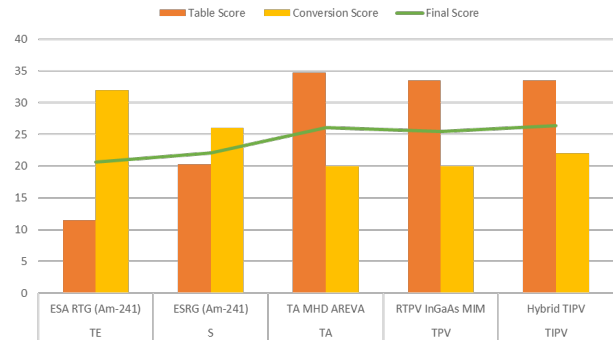
Conversion Type	System	Table Score	Conversion Score	Final Score	Rank
TE	ESA RTG (Am-241)	11.82	32.00	20.90	5
S	ESRG (Am-241)	20.63	26.00	22.24	4
TA	TA MHD AREVA	34.39	20.00	25.94	2
TPV	RTPV InGaAs MIM	33.17	20.00	25.35	3
TIPV	Hybrid TIPV	33.50	22.00	26.47	1

**Fig. 6.** Decision matrix and scores for new options.

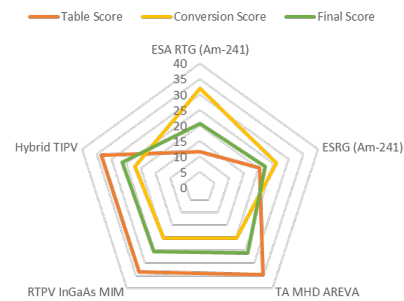
The top two technologies not currently in-development by TM are the Hybrid Thermionic-Thermophotovoltaic (TIPV) system and Thermoacoustic-Magneto Hydrodynamic (TA-MHD) generator. The hybrid thermionic-thermophotovoltaic system appears more promising than thermophotovoltaics or thermionics alone and may be beneficial to the RPS Program. The thermoacoustic coupled magneto-hydrodynamic generator is a promising system which may surpass current, in-development dynamic systems.

An advanced RTPV system with improvements made to supporting technologies may also be considered. Depending on specific RPS goals, this matrix can be altered by increasing or decreasing the scale of conversion method values so that the Conversion Scores are greater or lesser than the Table Score range. A higher Conversion Score scale would tip the final rankings in favor of RTG technologies more heavily due to their system advantages of high TRL, low complexity, high modularity and proven life.

**Thermal Conversion Systems (View 1)**



**Thermal Conversion Systems (View 2)**



**Fig. 7.** Bar chart (View 1) and radar chart (View 2) of separated new technology scores.

### V.A. Hybrid TIPV

The Hybrid TIPV system was proposed in 2016 by Datas (Ref. 7). Further research into this technology has been done in recent years with a study on a Thermionic-

enhanced near-field TPV convertor published in 2019 (Ref. 8). One promising aspect of a hybrid TI and TPV technology is that it eliminates the penalty for ohmic resistance found in typical RTPVs. One of the main concerns with TPV technologies are low power densities, however TIPV appears to reach higher values than TPV alone. “Ideal” values for TPV are usually estimated between 15-20% efficiency and  $>1\text{W}/\text{cm}^2$  power density, though testing usually finds these values difficult to obtain due to series resistance. The “real” TPV efficiencies in this temperature range which account for ohmic losses are between 5-10% efficiency. Thermionics typically require very high temperatures ( $>1300\text{K}$ ) to reach competitive system efficiencies, but TIPV may produce substantial power at much lower emitter temperatures (Ref. 9). The power output and efficiency for TIPV at emitter temperatures between 1000-1200K is very good compared to either system alone. A hybrid TIPV RPS may reach system efficiencies three times higher than the MMRTG and possible power density of  $6.73\text{ W}/\text{cm}^2$ .

#### **V.B. Thermoacoustic Magneto-Hydrodynamic Generator**

The TA-MHD system is based on a thermoacoustic engine (AREVA) which converts heat into mechanical energy, and a magneto-hydrodynamic generator (Hekyom) which converts mechanical energy into electrical energy using the Brayton cycle (Ref. 6). The thermoacoustic loop, or tubes, are coupled with an MHD generator that uses liquid sodium with the cold source above 400K (Ref. 10). Thermoacoustic effects and the oscillation of the liquid metal (sodium) are used to produce power. An electrical current flows into the liquid metal, and the vibration of liquid sodium interacts with a magnetic field to create an AC electrical current moving through the thermoacoustic loop. The TA-MHD is being researched by the ESA using Am-241. Using americium, the TA-MHD is estimated to have a specific power of 1.2 W/kg. The MMRTG using Pu-238 has a specific power of 2.5 W/kg, but the proposed TA-MHD generator would reach substantially higher specific power values using plutonium as a fuel source (Ref. 3). A benefit to this system is its lack of moving parts as it relies only on the oscillation of fluids, though a liquid-gas interface is challenging to develop.

#### **V.C. RTPV System**

Extensive research has been done in recent years to improve potential RTPV systems, though they still suffer from low rejection temperatures. A few different ways to improve TPV are using disk radiators instead of radiator fins to reject heat, changing the fuel geometry, increasing packing factor, using improved coatings (Ref. 11), and implementing spectral controls. Rather than using a cubic

geometry, a 3x3 arrangement of cylindrical fuel rods could improve overall RPS system efficiency by 39% (Ref. 12). The packing factor (PF) is the volume ratio between the radioisotope fuel region and overall heat source module. Increasing PF from 0.1 to 0.7 may result in a 23% increase in efficiency (Ref. 13). Some advanced cells have been investigated, with the InGaAs monolithic integrated module (MIM) cell being the most promising and having the potential to substantially exceed MMRTG performance with five times the specific power and three times the system efficiency (Ref. 14). RTPV would also make a good candidate for exploration of alternative fuels. It is important to note that the heat source accounts for ~70% of the system mass on an RTPV generator (Ref. 14). With a short half-life of 138 days and high decay heat of 140 W/g (compared to 0.57 W/g for Pu-238), Polonium-210 could be used for short duration missions to reduce overall system weight and greatly improve specific power.

## **VI. CONCLUSIONS**

NASA’s Radioisotope Power Systems Program is currently working to mature several research technologies including dynamic power convertors, advanced thermoelectric materials, and a thermo-electrochemical conversion system. A survey of heritage technologies as well as comparative analysis of potential new RPS research technologies was performed, resulting in the ranking and downselection of results. After a thorough decision-making process was established, the top three systems recommended for further investigation are a hybrid thermionic-thermophotovoltaic system, a thermoacoustic coupled magneto-hydrodynamic generator, and a modified RTPV system. The thermionic-enhanced near-field thermophotovoltaic (nTIPV) system is predicted to perform better than a TI or TPV system by itself, and potentially compete with current thermoelectric and dynamic convertors. The TA-MHD generator is also worthy of note. Using Pu-238 rather than Am-241, this system becomes comparable to current NASA investments within dynamic energy conversion.

## **ACKNOWLEDGMENTS**

This work was supported by the NASA Science Missions Directorate’s Radioisotope Power Systems Program office at NASA Glenn Research Center and part of this work was performed at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration. P.M. thanks the Universities Space Research Association for their sponsorship, and the Radioisotope Power Systems Program for their support.

## **REFERENCES**

1. A. Datas & A. Marti, "Thermophotovoltaic energy in space applications: Review and future potential," *Solar Energy Materials and Solar Cells*, **161**, 285-296 (2017). DOI:10.1016/j.solmat.2016.12.007.
2. T. Caillat, S. Pinkowski, I. Chi, C.-K. Huang, K. Smith, K. Yu, J. Paik, P. Gogna, B. Phan, E. Heian, T. Holgate, Y. Song, J. VanderVeer, R. Bennett, S. Keyser, P. Frye, K. Wefers, M. Hoffmann, and M. Deminico, "An Update on the Development of Skutterudite-based Thermoelectric Technology for Integration into a Potential Enhanced Multi-Mission Radioisotope Thermoelectric Generator (eMMRTG)", *Proceedings of the Nuclear and Emerging Technologies for Space*, Knoxville, TN, April 6-9 2020, 23, (2020).
3. A. Mazzetti, M. Gianotti Pret, G. Pinarello, L. Celotti, M. Piskacev, A. Cowley, "Heat to electricity conversion systems for moon exploration scenarios: A review of space and ground technologies", *Acta Astronautica*, **156**, 162-186 (2018). DOI:10.1016/j.actaastro.2018.09.025.
4. L. Johnson, "Johnson Thermo-Electrochemical Converter (JTEC) as a Heat to Electric Generator for Nuclear Power Systems", *Proceedings of the Nuclear and Emerging Technologies for Space*, Richland, WA, Feb 25-28 2019, (2019).
5. A. Alemany, A. Krauze, M. Al Radi, "Thermo acoustic – MHD electrical Generator", *Energy Procedia*, **6**, 92-100 (2011). DOI:10.1016/j.egypro.2011.05.011.
6. A. Alemany, M. Francois, E. Roy, J. Freiberg, G. Poli, E. Zeminiani, S. Eckert, "Space Thermoacoustic Radio-Isotopic Power System Third Review meeting with Area Brussels January 15 2016", Retrieved December 20, 2021, from <https://cordis.europa.eu/docs/results/312/312639/final1-review-meeting-of-january-15-2016.pdf>
7. A. Datas, "Hybrid thermionic-photovoltaic converter", *Appl. Phys. Lett.*, **108**, 143503 (2016). DOI: 10.1063/1.4945712.
8. A. Datas and R. Vaillon, "Thermionic-enhanced near-field thermophotovoltaics for medium-grade heat sources", *Appl. Phys. Lett.*, **114**, 133501 (2019). DOI:10.1063/1.5078602.
9. M. F. Campbell, T. J. Celenza, F. Schmitt, J.W. Schwede, I. Bargatin, "Progress Toward High Power Output in Thermionic Energy Converters", *Adv. Sci.* **8**, 2003812, (2021). DOI:10.1002/advs.202003812.
10. A. Alemany, M. Francois, K. de Blok, J. Roux, G. Poli, E. Zeminiani, E. Gaia, P. Jeantet, E. Roy, C. Chillet, J. Freiberg, R. Nikoluškins, G. Gerbeth, S. Eckert, "Space thermoacoustic radio-isotopic power system: SpaceTRIPS", *Proceedings of the Third International Workshop on Thermoacoustics*, University of Twente, Enschede, October 26-27 2015, (2015). DOI:10.3990/2.284.
11. H. Wang, Z. Xu, Z. Yuan, K. Liu, C. Meng, X. Tang, "High-temperature and radiation-resistant spinel-type ferrite coating for thermo-optical conversion in radioisotope thermophotovoltaic generators", *Energy*, **239**, Part D, 122255 (2022). DOI: 10.1016/j.energy.2021.122255.
12. S.J. Cheon, S.G. Hong, J.H. Lee, Y.S. Nam, "Design and performance analysis of a 500-W heat source for radioisotope thermophotovoltaic converters", *International Journal of Energy Research*, **42**(2), 817-829 (2018). DOI:10.1002/er.3889.
13. J. Lee, S. Cheon, S. Hong, Y. Nam, "A radioisotope thermophotovoltaic converter with nanophotonic emitters and filters", *International Journal of Heat and Mass Transfer*, **108**, Part A, 1115-1125 (2017). DOI:10.1016/j.ijheatmasstransfer.2016.12.049.
14. X. Wang, R. Liang, P. Fisher, W. Chan, J. Xu, "Radioisotope Thermophotovoltaic Generator Design Methods and Performance Estimates for Space Missions", *Journal of Propulsion and Power*, **36** (4), 593-603, (2020). DOI: 10.2514/1.B37623